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DELIVERABLE 1-1
CORE DESCRIPTIONS, CORE PHOTOGRAPHS, AND CORE ANALYSIS: LISBON FIELD, SAN JUAN COUNTY, UTAH

THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

Submitted by:
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DISCLAIMER

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by

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INTRODUCTION

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil from six fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado. All of these fields are currently operated by small, independent producers. There have been no new discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves. These goals are designed to assist the independent producers and explorers who have limited financial and personnel resources.

Exploring for the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition requires expensive, three-dimensional (3D) seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in trying new techniques.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. Acquiring this information or producing these studies would save cash and manpower resources which independents simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation, and therefore increase the chance of successfully finding new accumulations of Leadville oil.

GEOLOGIC SETTING

Paradox Basin Overview

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian. The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the

Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2). Most Leadville production is from the Paradox fold and fault belt (figure 3).

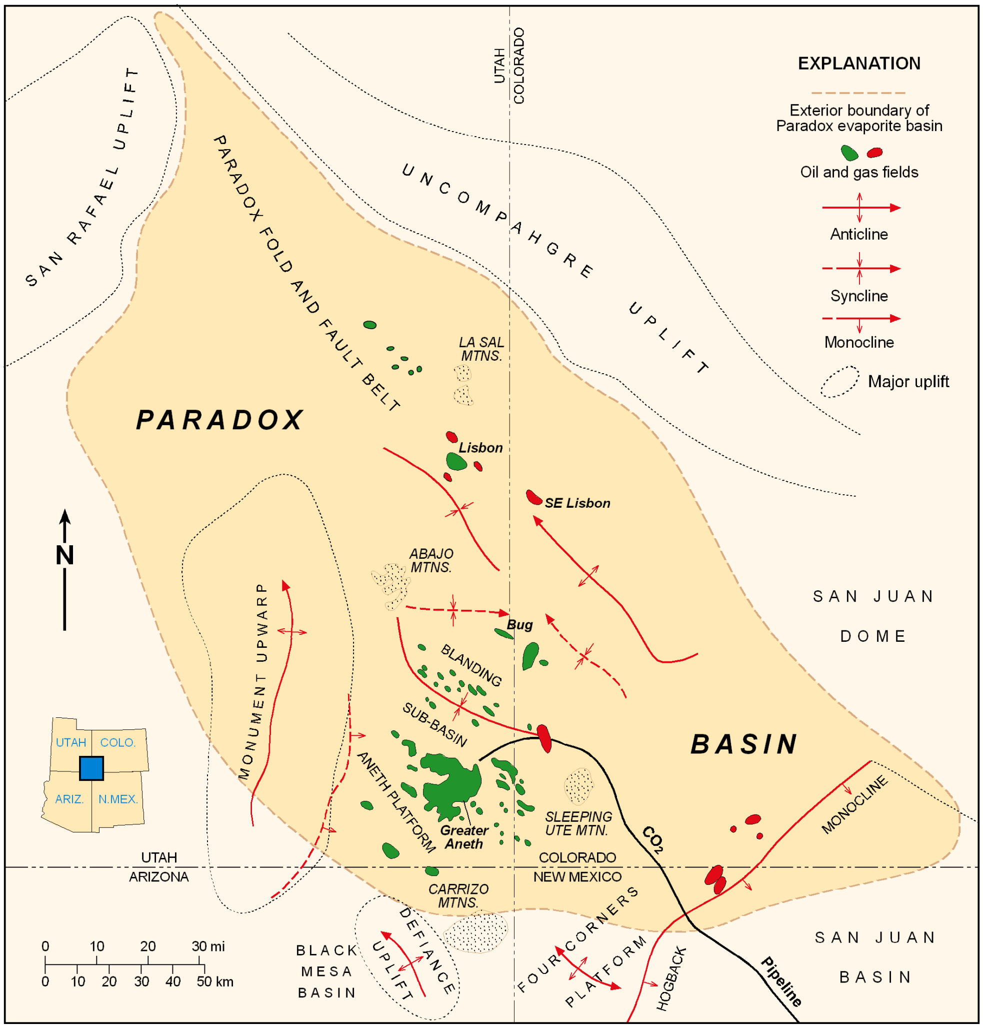

Figure 1. Oil and gas fields in the Paradox Basin of Utah and Colorado.

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults and fractures 1700 to 1600 Ma (Stevenson and Baars, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical, thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian. A series of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands

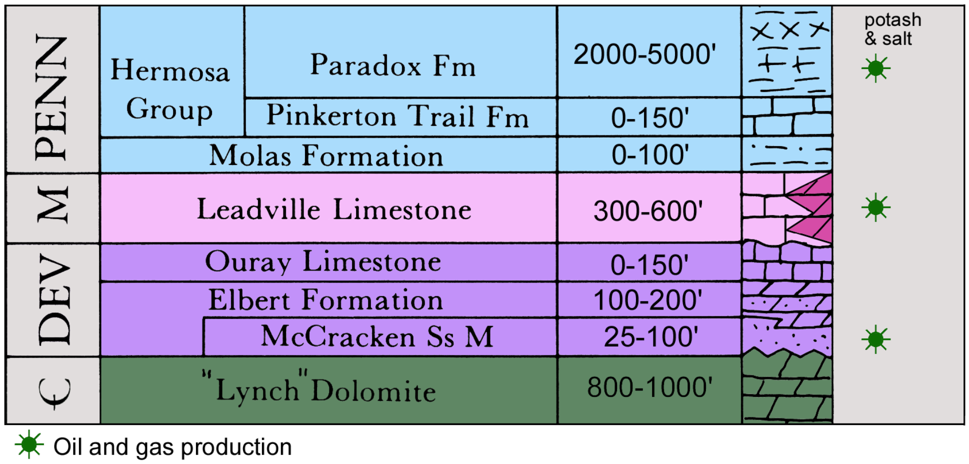

Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle, reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The Paradox Basin is surrounded by other uplifts and basins, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt flowage, dissolution and collapse, and (3) regional uplift (Doelling, 2000).

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

Regional Leadville Facies

The Mississippian (late Kinderhookian through Osagean to early Meramecian time) Leadville Limestone is a shallow, open marine, carbonate-shelf deposit (figure 5). The western part of the Paradox fold and fault belt includes a regional, reflux-dolomitized, interior bank facies containing Waulsortian mounds (Welsh and Bissell, 1979). During Late Mississippian time, the entire carbonate platform in southeastern Utah and southwestern Colorado was subjected to subaerial erosion resulting in formation of a lateritic regolith (Welsh and Bissell, 1979). This regolith and associated carbonate dissolution is an important factor in Leadville reservoir potential (figure 6). Solution breccia and karstified surfaces are common, including possible local development of cavernous zones (Fouret, 1982, 1996).

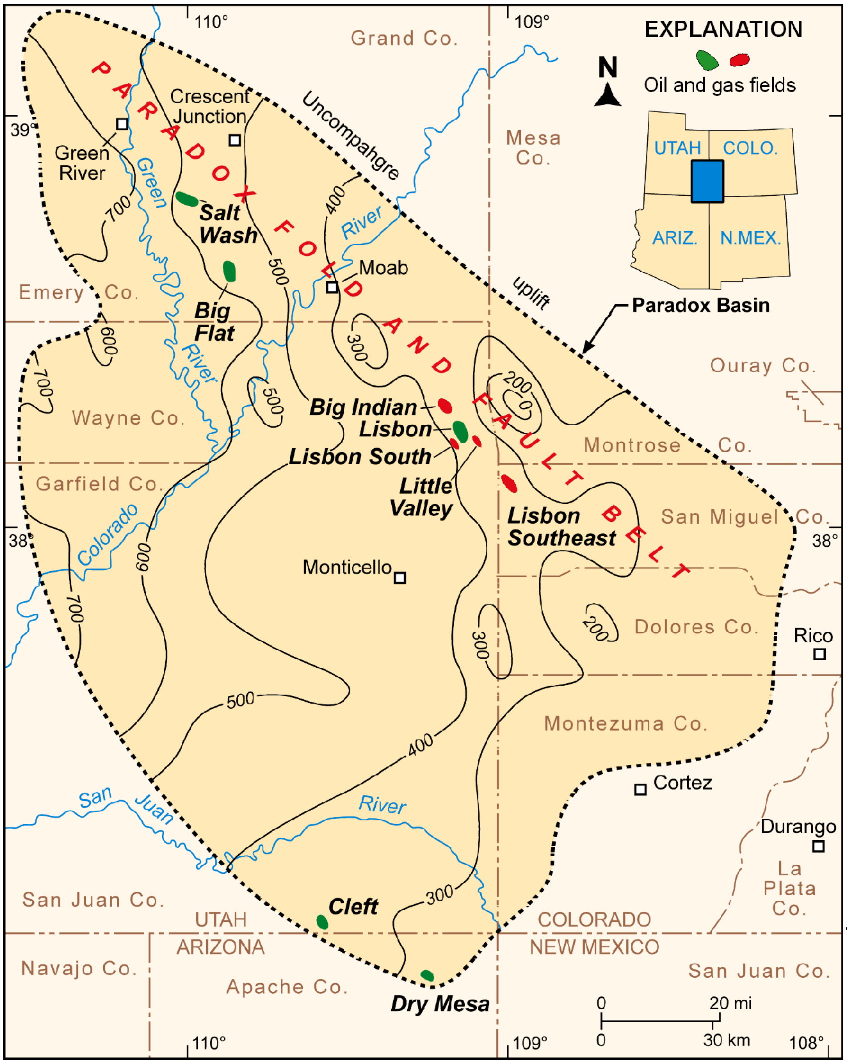

Figure 3. Location of fields that produce from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

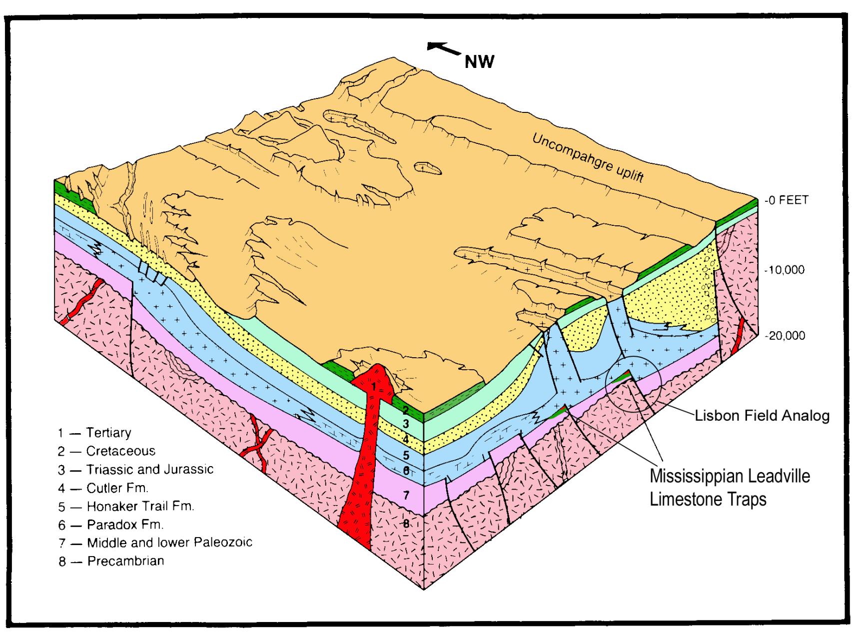

Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

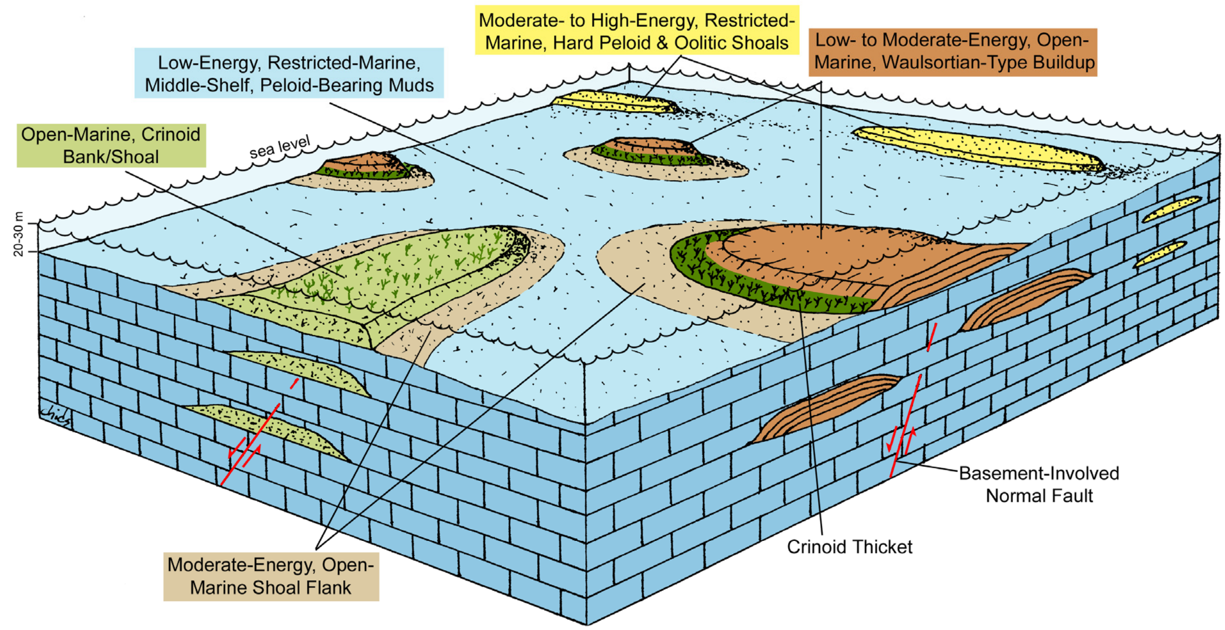

Figure 5. Block diagram displaying major depositional facies, as determined from core, for the Leadville Limestone, Lisbon field, San Juan County, Utah.

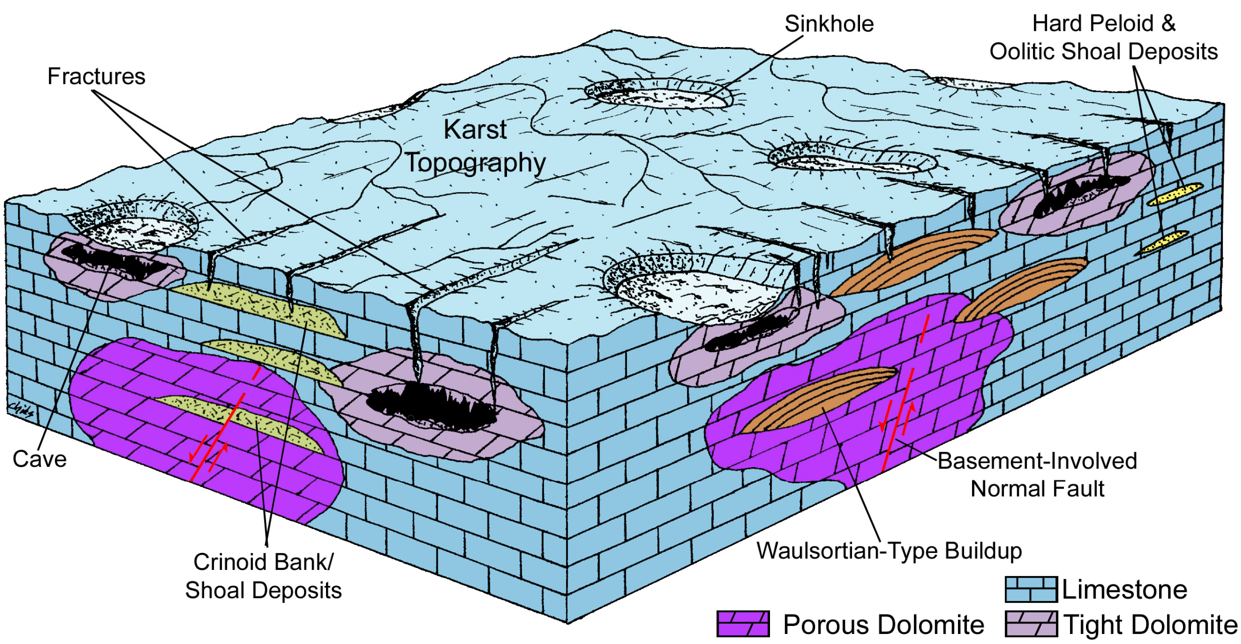

Figure 6. Block diagram displaying post-Leadville karst and fracture overprint.

The Leadville Limestone thins from more than 700 feet (230 m) in the northwest corner of the Paradox Basin to less than 200 feet (70 m) in the southeast corner (Morgan, 1993) (figure 3). Thinning is a result of both depositional onlap onto the Mississippian cratonic shelf and erosion. The Leadville is overlain by the Pennsylvanian Molas Formation and underlain by the Devonian Ouray Limestone (figure 2).

Periodic movement along northwest-trending faults affected deposition of the Leadville Limestone. Crinoid banks or mounds, the primary reservoir facies (figure 5), accumulated in shallow-water environments on upthrown fault blocks or other paleotopographic highs. In areas of greatest paleorelief, the Leadville is completely missing as a result of non-deposition or subsequent erosion (Baars, 1966).

The Leadville Limestone is divided into two members separated by an intraformational disconformity. The dolomitic lower member is composed of mudstone, wackestone, packstone, and grainstone deposited in shallow-marine, subtidal, supratidal, and intertidal environments (Fouret, 1982, 1996). Fossils include crinoids, fenestrate bryozoans, and brachiopods. Locally, mud-supported boundstone creates buildups or mud mounds (Waulsortian facies), involving growth of "algae" (Wilson, 1975; Ahr, 1989; Fouret, 1982, 1996). The upper member is composed of mudstone, packstone, grainstones (limestone and dolomite), and terrigenous clastics also deposited in subtidal, supratidal, and intertidal environments (Fouret, 1982, 1996). Fossils include crinoids and rugose coral. Reservoir rocks are crinoid-bearing packstone (Baars, 1966).

LISBON CASE STUDY FIELD, SAN JUAN COUNTY, UTAH

Introduction and Field Synopsis

Lisbon field, San Juan County, Utah (figure 3) accounts for most of the Leadville oil production in the Paradox Basin. A wealth of Lisbon core, petrographic, and other data is available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the Paradox Basin. Therefore, we selected Lisbon as the major case-study field for the Leadville Limestone project. This evaluation included data collection, core descriptions, plots of petrophysical data (core-plug porosity and permeability), and core photographs as summarized in this report.

The Lisbon trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and Prather, 1981) (figure 7). Several minor, northeast-trending normal faults divide the Lisbon Leadville reservoir into segments.

Producing units in Lisbon field contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes fracturing, autobrecciation, karst development, hydrothermal dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. Porosity averages 6 percent in intercrystalline and moldic networks enhanced by fractures; permeability averages 22 millidarcies (mD). The drive mechanism is an expanding gas cap and

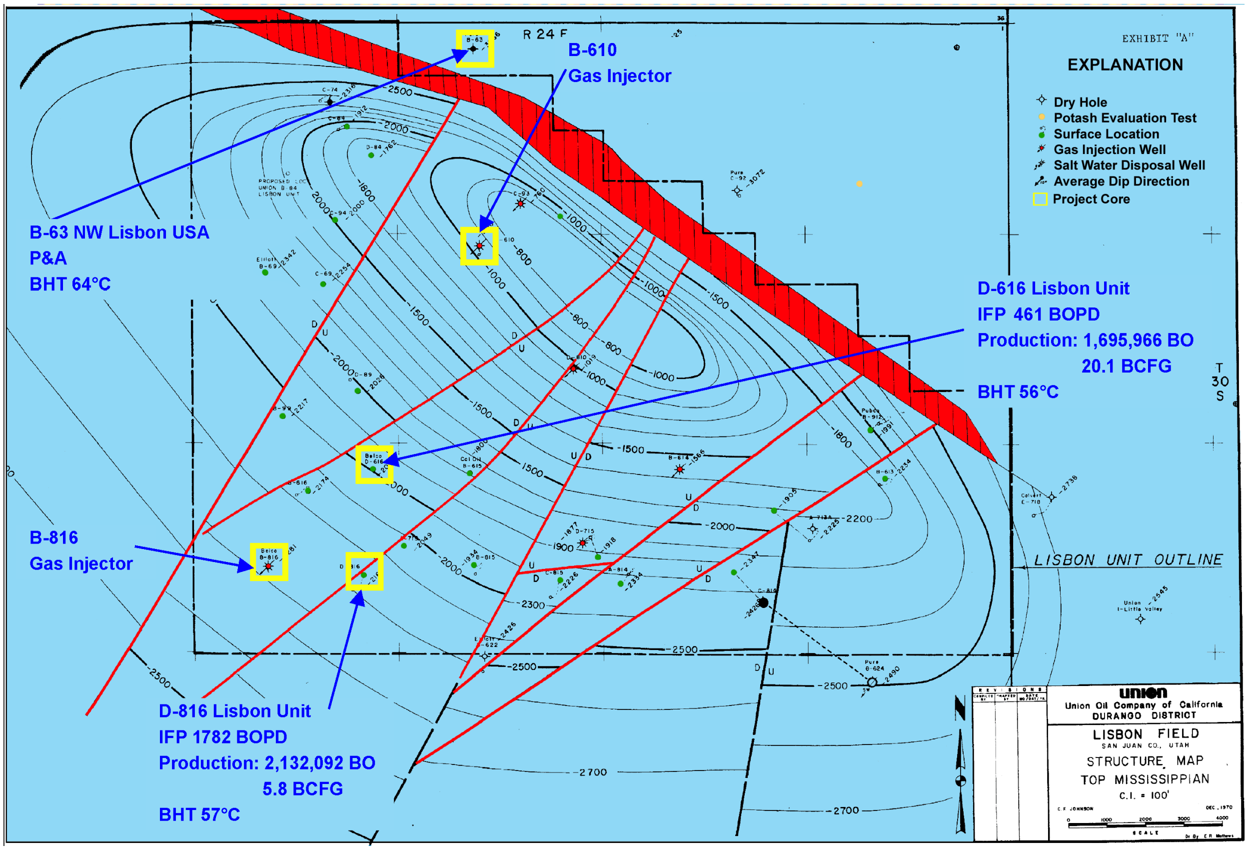

Figure 7. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.). Also displayed are wells from which cores were described in this study.

gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 133 to 189ºF (56-87ºC).

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., SLBL&M (figure 7), with an initial flowing potential of 179 bbls of oil per day (BOPD) (28 m^3) and 4376 thousand cubic feet of gas per day (124 MCMPD). The original reservoir field pressure was 2982 pounds per square inch (psi [20,560 kPa]) (Clark, 1978). There are currently 22 producing (or shut-in wells), 11 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of March 31, 2006, was 51,145,231 bbls of oil (8,132,092 m^3), 785.4 billion cubic feet of gas (BCFG) (22.2 BCMG) (cycled gas), and 50,073,622 bbls of water (7,961,706 m^3) (Utah Division of Oil, Gas and Mining, 2006). Gas that was re-injected into the crest of the structure to control pressure decline is now being produced.

Three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification), and (3) fracturing. The extent of these factors and how they combine affect the degree to which they create barriers to fluid flow.

Data Collection and Compilation

Geophysical well logs, cores and cuttings, reservoir data, various reservoir maps, and other information from Lisbon field development wells were collected by the UGS. Well locations, formation tops, production data, completion tests, basic core analysis, porosity and permeability data, and other data were compiled and entered in a database developed by the UGS. This database, INTEGRAL, is a geologic-information database that links a diverse set of geologic data to records using MS Access™. The database is designed so that geological information, such as lithology, petrophysical analyses, or depositional environment, can be exported to software programs to produce cross sections, strip logs, lithofacies maps, various graphs, and other types of presentations. The database containing information on the geological reservoir characterization case study as well as later regional correlations will be available at the UGS's Leadville Limestone project Web site at the conclusion of the project.

CORE DESCRIPTION AND PHOTOGRAPHY

All available conventional cores from Lisbon field (figure 7, table 1) were described (plates 1 through 5, in pocket) and photographed (Appendices A and B). Special emphasis was placed on identifying the flow unit's bounding surfaces and depositional environments. The core descriptions follow the guidelines of Bebout and Loucks (1984), which include (1) basic porosity types, (2) mineral composition in percentage, (3) nature of contacts, (4) carbonate structures, (5) carbonate textures in percentage, (6) carbonate fabrics, (7) grain size (dolomite), (8) fractures, (9) color, (10) fossils, (11) cement, and (12) depositional environment. Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes.

Table 1. List of well conventional slabbed core examined and described from the Leadville Limestone, Lisbon field, San Juan County, Utah.*

Well	Location	API No.	Core Interval (feet)	Thin Sections
Lisbon D-816	NE SE 16, T. 30 S., R. 24 E.	43-037-16253	8417-8450	15
Lisbon D-616	C NE NE 16, T. 30 S., R. 24 E.	43-037-15049	8300-9110	13
NW Lisbon B-63	NE NW 3, T. 30 S., R. 24 E.	43-037-11339	9934-10,005	14
Lisbon B-816	NE SW 16, T. 30 S., R. 24 E.	43-037-16244	8463-8697	22
Lisbon B-610	NE NW 10, T. 30 S., R. 24 E.	43-037-16469	7590-8001.5	18

*Repository: Utah Core Research Center.

Geological characterization on a local scale focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization within Lisbon field. This utilized representative core to characterize and various untested intervals in the field for possible additional completion attempts.

CORE ANALYSIS

Porosity and permeability data from core plugs were obtained from the five well cores described (table 1). Cross plots (Appendix C) of these data are used to (1) determine the most effective pore systems for oil storage versus drainage, (2) identify reservoir heterogeneity, (3) predict potential untested compartments, (4) infer porosity and permeability trends where core-plug data are not available, and (5) match diagenetic processes, pore types, mineralogy, and other attributes to porosity and permeability distribution. Porosity and permeability cross plots were constructed using the available data.

These cross plots from the Leadville Limestone in Lisbon field show that the dominant pore types are intercrystalline, moldic, fracture, and channel. The plots show two distinct populations of dolomites with respect to permeability and petrographic character. The early, finely crystalline dolomites (with or without isolated molds) display low permeability. The coarser, late dolomites (with or without late dissolution) display high permeability. In addition, analysis of the plots show that those zones that have been dolomitized have better reservoir potential than those that remain limestone, even where the limestone has been fractured and brecciated.

LISBON FIELD FACIES

Three depositional facies have been identified from Leadville Limestone cores we described from the Lisbon case-study field (figure 5). Recognizing and mapping of these facies regionally will delineate prospective reservoir trends containing porous and productive buildups or zones. Leadville facies include open marine, middle shelf, and restricted marine.

Open Marine

Open-marine facies are represented by crinoidal banks or shoals and Waulsortian-type buildups (figure 5). Crinoidal banks and shoals are common throughout Leadville deposition, often located on paleotopographic highs developed along the upthrown side of older basement-involved faults. This facies represents a high-energy environment with well-circulated, normal-marine salinity water in a subtidal setting. Wave action was strong (leaving broken crinoid columns and winnowing out mud) to moderate (leaving articulated crinoid columnals and some muddy matrix). Low to medium cross-bedding is common. Crinoid columnals were not transported far from the thickets where they grew. Rugose corals were also abundant in this environment. According to Wilson (1975), crinoid columnals or segments were covered with organic matter which allowed them to float until accumulating on nearby shoals and banks. Water depths ranged from 5 feet to 45 feet (1.5-14 m). The depositional fabrics of crinoidal banks and shoals include grainstone and packstone (figure 8). Rocks representing crinoidal banks and shoals typically contain the following diagnostic constituents: dominately crinoids and rugose corals, and lesser amounts of broken fenestrate bryozoans, brachiopods, ostracods, and endothyroid forams as skeletal debris. Rock units having this facies constitute a significant reservoir potential, having both effective porosity and permeability when dissolution of skeletal grains, followed by dolomitization, has occurred.

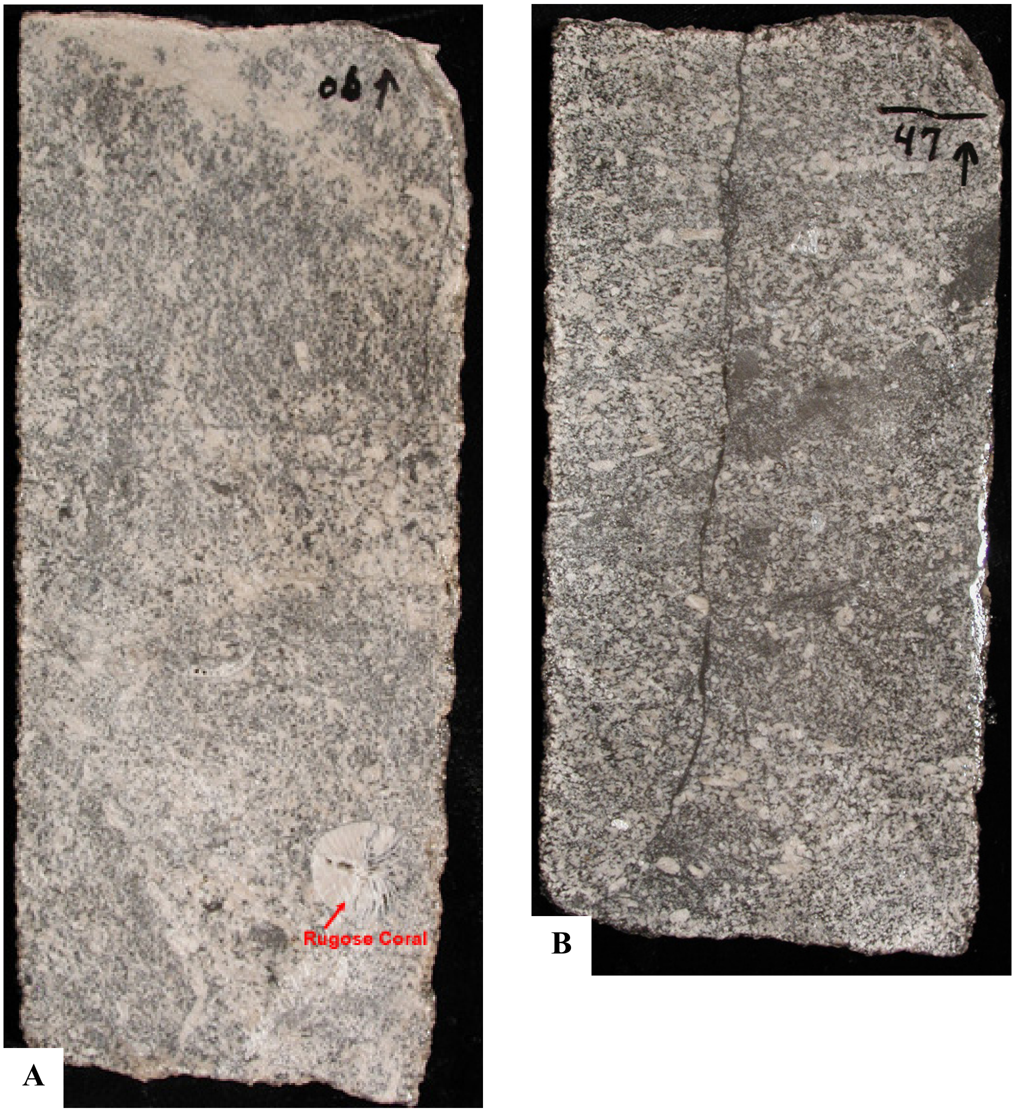

Figure 8. Typical crinoidal/skeletal grainstone/packstones representing high-energy, open-marine shoal facies, Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 7]). (A) Slabbed core from 8506.5 feet. Note the large rugose coral. (B) Slabbed core from 8547 feet.

Waulsortian buildups or mud mounds developed exclusively during the Mississippian in many parts of the world (Wilson, 1975) and Waulsortian-type buildups were first described in Lisbon field by Fouret (1982). They are steep-sloped tabular, knoll, or sheet forms composed of several generations of mud deposited in a subtidal setting (Lees and Miller, 1995; Fouret, 1982, 1996) (figure 5). The lime mud was precipitated by bacteria and fungal/cyanobacterial filaments (Lees and Miller, 1995). Cyanobacteria was a likely precursor to the green algae *Ivanovia* responsible for Pennsylvanian buildups in the Paradox Basin (Fouret, 1982, 1996). Crinoids and sheet-like fenestrate byrozoans, in the form of thickets, are associated with the deeper parts of the mud mounds and are indicative of well-circulated, normal-marine salinity. Water depths ranged from 60 to 90 feet (20-30 m). The thickets surrounded and helped to stabilize the mound. Burrowing organisms added a pelletal component to the mud, and burrowing often destroyed laminations or made them discontinuous. Individual mounds range from a few feet to tens of feet thick, and cover hundreds of feet in area with distinctive flank deposits. They form thick, extensive aggregates often located on paleotopographic highs associated with basement-involved faults (figure 5). This facies represents a low- to moderate-energy environment. The depositional fabrics of the Waulsortian-type buildups include mud-supported boundstone, packstone, and wackestone (figure 9). Rocks representing Waulsortian-type buildups typically contain the following diagnostic constituents: peloids, crinoids, bryozoans, and associated skeletal debris, and *stromatactis*. Rock units having this facies constitute a significant reservoir potential, having both effective porosity and permeability, especially after dolomitization. Waulsortian-type buildups are recognized in several additional cores described by Fouret (1982, 1996).

Shoal-flank facies are associated with both crinoid bank/shoal and Waulsortian-type buildup facies (figure 5). This facies represents a moderate-energy environment, again with well-circulated, normal-marine salinity water in a subtidal setting. Water depths ranged from 60 to 90 feet (20-30 m). In the shallower areas, wave action was strong to moderate, eroding the flanks of the shoals and mud mounds into a breccia. Bedding is generally absent in cores. The depositional fabrics of the shoal-flank facies include peloidal/skeletal packstone and

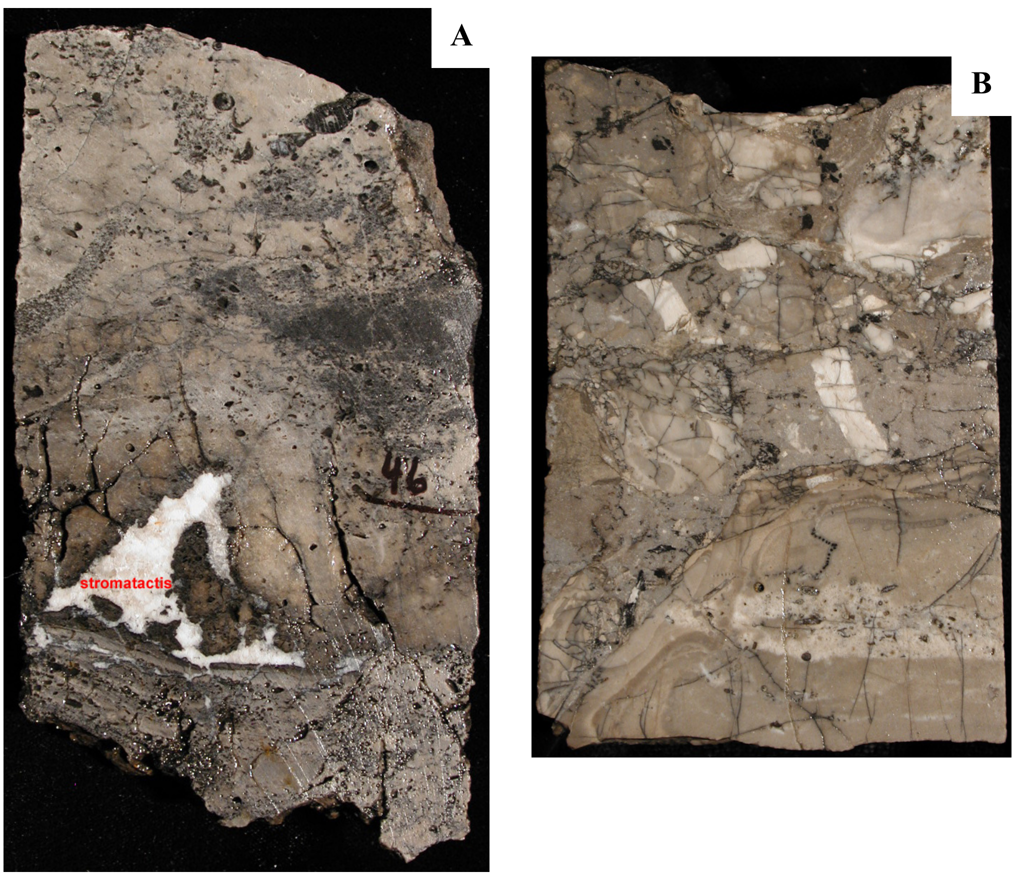

Figure 9. Typical peloidal/skeletal packstone/wackestones representing moderate- to low-energy, open-marine, Waulsortian-type buildup facies. (A) Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 7]); slabbed core from 8646 feet. (B) Lisbon No. D-616 (NE1/4NE1/4 section 16, T. 30 S., R. 24 E., SLBL&M); slabbed core from 8514 feet.

wackestone (figure 10). Rocks representing this facies typically contain the following diagnostic constituents: peloids, crinoids, bryozoans, brachiopods, and associated skeletal debris, and talus, depositional breccia, and conglomerate (Fouret, 1982, 1996). Rock units having shoal-flank facies constitute a limited reservoir potential, having little effective porosity and permeability.

Restricted Marine

Restricted-marine facies are represented by "hard" peloid and oolitic shoals that developed as a result of regularly agitated, shallow-marine processes on the shelf (figure 5). Like crinoidal banks and Waulsortian-type buildups, hard peloid and oolitic shoals are common throughout Leadville deposition, especially on paleotopographic highs. This facies represents a moderate- to high-energy environment, with moderately well-circulated water in an intertidal setting. The water probably had slightly elevated salinity compared to the other facies. Sediment deposition and modification probably occurred in water depths ranging from near sea level to 20 feet (6 m) below sea level. Wave action winnowed out mud leaving various well-sorted grains. Characteristic features of this facies include medium-scale cross-bedding and bar-type carbonate sand-body morphologies that formed not only shoals, but beaches and tidal bars (Fouret, 1982). Well-developed ooids were produced from movement of particles over algal or cyanobacterial mats by intertidal currents and continuous wave action (Mitchell, 1961; Fouret, 1982).

The depositional fabrics of the restricted-marine facies include grainstone and packstone (figure 11). Rocks representing this facies typically contain the following diagnostic constituents: ooids, coated grains, and hard pelloids. Fossils are relatively rare.

Rock units having restricted-marine facies constitute good reservoir potential. Remnants of visible interparticle and moldic porosity may be present in this facies. Dolomitization significantly increases the reservoir quality of this facies.

Middle Shelf

Middle-shelf facies covered extensive areas across the shallow shelf. This facies represents a low-energy, often restricted-marine environment (figure 5). Mud and some sand were deposited in subtidal (burrowed), inter-buildup/shoal setting. Water depths ranged from 60 to 90 feet (20-30 m).

The depositional fabrics of the middle-shelf facies include wackestone and mudstone (figure 12). The most common is bioturbated lime to dolomitic mudstone with sub-horizontal feeding burrows. Rocks representing this facies typically contain the following diagnostic constituents: soft pellet muds, "soft" peloids, grain aggregates, crinoids and associated skeletal debris, and fusulinids.

Rock units having middle-shelf facies act as barriers and baffles to fluid flow, having very little effective porosity and permeability. There are few megafossils and little visible matrix porosity, with the exception of an occasional moldic pore. However, recognizing this facies is important because low-energy carbonates of the middle shelf form the substrate for the development of the higher energy crinoid banks, oolitic/hard peloid shoals, and Waulsortian-type buildups (figure 5). The middle-shelf facies can contain reservoir-quality rocks if dolomitized.

Figure 10. Typical peloidal/ skeletal packstone/wackestone representing moderate-energy, open-marine, shoal-flank facies. Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 7]); slabbed core from 8521 feet.

Figure 11. Typical peloidal grainstone/packstone representing moderate-energy, restricted-marine, "hard" peloid shoal facies. Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 7]); slabbed core from 8463 feet.

Figure 12. Typical skeletal/"soft" peloidal wackestone/mudstone representing low-energy, restricted-marine, middle-shelf facies. Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 7]); slabbed core from 8549 feet.

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